

Particle production from off-shell nucleons

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Abstract

Particle production in equilibrium and nonequilibrium quantum systems is calculated. The effects of the off-shell propagation of nucleons in medium on the particle production are discussed. Comparison to the semiclassical production rate is given.

The production of mesons and hard photons in intermediate energy heavy ion collisions is considered to be sensitive to the collision dynamics and to medium effects. The medium effects can be two-fold. First, the properties of the mesons produced and propagating in the high density region created in the collision can be modified. Also particle production rates can be modified by the fact that the colliding nucleons are interacting with the surrounding nuclear medium. This can lead to a different production rate obtained from nucleon collisions in dense medium than in free nucleon-nucleon collisions.

In the work [1] we presented the results of a calculation of the meson production rate in a nonequilibrium system of interacting nucleons. The nonequilibrium dynamics is described by the one-body Kadanoff-Baym equations for the real-time nonequilibrium fermion Green's functions. The numerical solution is obtained for a spatially homogeneous system with the initial momentum distribution corresponding two Fermi spheres, following [2]. The quantum rate of the production of mesons is then calculated using the corresponding Kadanoff-Baym equations for mesons with the one-loop self-energy. The meson production rate takes the form :

$$\begin{aligned} \frac{dN(p, t)}{d^3p dt} = 2\mathcal{R}e \left(- \int_{t_0}^t dt' \Pi^<(p, t, t') D_0^>(p, t', t) \right. \\ \left. + \int_{t_0}^{t_0 - i\tau_0} dt' \Pi^<(p, t, t') D_0^>(p, t', t) \right) , \end{aligned} \quad (1)$$

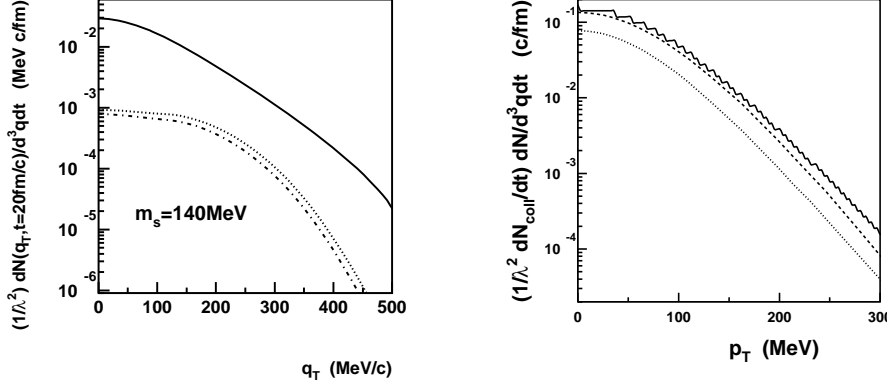


Fig. 1. (left panel) The meson production rate at $t = 20$ fm/c from the nonequilibrium evolution at the collision energy of 180 MeV. The solid line denotes the quantum production rate. The dotted line is the semiclassical production rate using the fermion momentum distribution from the quantum evolution and the dashed-dotted line is the one using the momentum distributions obtained from a BUU calculation. (right panel) Production rate of mesons of mass 140 MeV at equilibrium. Quantum, semiclassical and semiclassical with unperturbed momentum distribution are presented with solid, dashed and dotted lines respectively.

where the meson one-loop self energy is given by the fermion Green's functions G :

$$\Pi^<(p, t_1, t_2) = -i\lambda^2 \int \frac{d^3q}{(2\pi)^3} G^<(p - q, t_1, t_2) G^>(q, t_2, t_1) . \quad (2)$$

The interaction strength λ can in general include momentum dependence through form factors and derivative couplings. In the following we will compare the quantum and semiclassical production rates divided by λ^2 . The semiclassical production rate was obtained by cutting the meson one-loop self-energy diagram with self-energy insertion on the fermion line. The matrix element for the production of a meson with momentum q and energy Ω_q can be written using the retarded fermion Green's functions G^R :

$$|M|^2 = 4\lambda^2 V(p_2 - p_4)^2 \left(|G^R(\omega_{p_1} - \Omega_q, p_1 - q)|^2 + |G^R(\omega_{p_3} + \Omega_q, p_3 + q)|^2 \right) , \quad (3)$$

where two nucleons with initial momenta p_1, p_2 scatter into momenta p_3 and p_4 . In Ref. [1] we used a very simple form of the retarded propagator including only a constant imaginary fermion self-energy.

In order to study the different approaches to the production rates more care-

fully we repeated the calculation in thermal equilibrium. The numerical effort is much reduced, allowing for more precise results. Also we notice [1] that it is very difficult to define a nonequilibrium quantum production rate because a time average is needed in order to define this quantity. The equilibrium finite temperature system is solved by iterating the real-time relations between the fermion Green's functions and the spectral density, where the spectral density was given by the Born self-energy depending itself on the fermion Green's functions ($T = 20\text{MeV}$, $\mu = 30\text{MeV}$, the chemical potential can also include a momentum independent mean-field). The quantum meson production rate is calculated from the one-loop meson self energy :

$$\frac{dN(q)}{d^3q dt} = \mathcal{I}m\Pi^<(\Omega_q, q) \quad (4)$$

and is scaled by the number of collisions :

$$\frac{dN_{coll}}{dt} = \int \frac{d^3p}{(2\pi)^3} \frac{d\omega}{2\pi} G^<(\omega, p) \Sigma^>(\omega, p) , \quad (5)$$

where Σ is the fermion self-energy. The semiclassical production rate is calculated using the matrix element (3) with the retarded Green's function extracted from the quantum calculations. The momentum distribution of fermions is taken using the quasiparticle fermion energies $f(\omega_p)$ or using the free dispersion relation $f(p^2/2m)$ (unperturbed momentum distributions in equilibrium). Here also the production rate is scaled by the number of nucleon collisions in the quasi-particle approximation. The results show a smaller difference between the semiclassical and quantum production rates than the less accurate nonequilibrium calculations. One should also note that the system studied in Ref. [1] is still not at equilibrium at $t = 20 \text{ fm}/c$. The differences start to be important for large momenta of the mesons or for mesons with high mass. Then the quantum treatment of the production rates is necessary and can have implications for the predictions on subthreshold meson production.

Another important effect of the medium on production rates can be seen for the production of soft particles [3]. The semiclassical production rate in vacuum diverges for soft mesons. In medium it leads to very high production rates. These are not realistic due to the requirement of a sufficient formation time for the produced particles between collisions. The use of a damping width in the retarded propagators regularizes this behavior. The result is identical to the quantum production rate with quasi-particle approximation for cut fermion lines. In the right panel of Fig.2 we show the comparison of the quantum production rate and the semiclassical production rates using the in medium and the vacuum matrix element. The results show the importance of taking correctly the medium effects into account when calculating the production

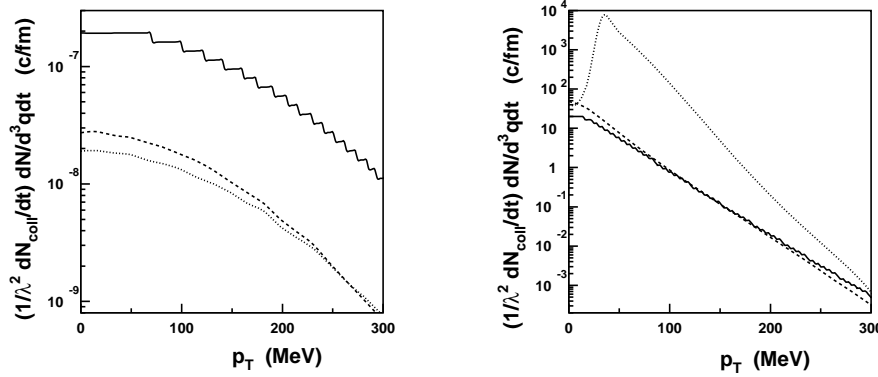


Fig. 2. (left panel) Production rate of mesons of mass 500 MeV at equilibrium. Quantum, semiclassical and semiclassical with unperturbed momentum distribution are presented with solid, dashed and dotted lines respectively. (right panel) Production rate of mesons of mass 20 MeV at equilibrium. Quantum, semiclassical and semiclassical with vacuum scattering matrix distribution are presented with solid, dashed and dotted lines respectively.

rates for soft particles. We found that both the real and the imaginary part of the self-energy in the retarded fermion propagator influence substantially the results for the production rate.

The calculations using the spectral function in equilibrium are numerical fast and accurate. They represent an alternative to the full solution of the Kadanoff-Baym equations, which is very difficult in homogeneous systems and impractical for a realistic description of nuclear collision dynamics. Instead it seems possible to use equations for the local spectral functions, equivalent to the gradient expansion of the Kadanoff-Baym equations.

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References

- [1] P. Bozek, Phys. Rev. C **56**, (1997) 1452.
- [2] P. Danielewicz Ann. Phys. (N.Y.) **152**, (1984) 305.
- [3] J. Knoll and N. Voskresenskii, Ann. Phys. (N.Y.) **249**, (1996) 532.